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FEASIBILITY ASSESSMENT OF RADIOLOCATION SERVICE SHARING WITH FI--ETC(U)
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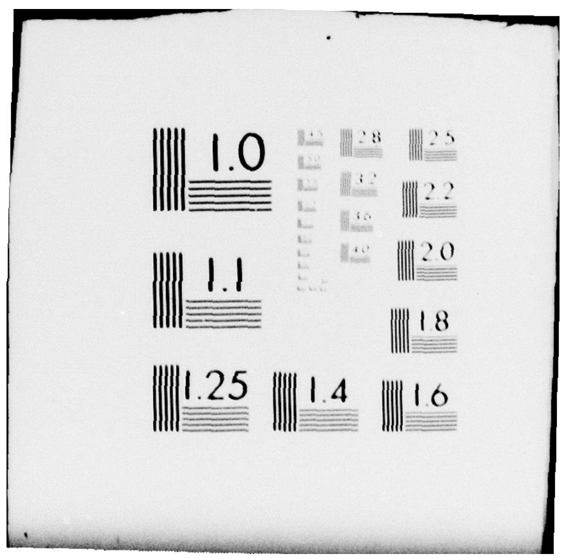
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Feasibility Assessment of Radiolocation Service Sharing With Fixed, Mobile, and Fixed-Satellite Services in 92- to 95-GHz Band

by
West E. Katzenstein
Electronic Warfare Department

JANUARY 1980

NAVAL WEAPONS CENTER
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Naval Weapons Center

AN ACTIVITY OF THE NAVAL MATERIAL COMMAND

FOREWORD

This study was undertaken by the Naval Weapons Center at the direction of the Director, Electromagnetic Spectrum Management, Office of the Chief of Naval Operations (OP-941F), under Task X0738100 in support of the U.S. Navy preparatory effort for the 1979 General World Administrative Radio Conference (GWARC) to be held in Geneva, Switzerland, in 1979. This document was approved at the Special Preparatory Meeting (SPM) of the International Radio Consultative Committee (CCIR) at Geneva, Switzerland, in November 1978, as source material for the SPM report. The SPM report provides the technical bases for the considerations of the GWARC.

This document is an analysis of the ability of the radiolocation service to share the 92- to 95-GHz band with the fixed, mobile, and fixed-satellite services. This analysis indicates that required separation distances between radiolocation and the other services are small and, hence, that sharing is feasible.

This report has been reviewed for technical accuracy by members of study groups 1 and 1A of the United States' CCIR structure and by John B. Seybold of the Naval Weapons Center, in addition to the technical approval it received at the SPM.

Approved by
G. R. SCHIEFER, *Head*
Electronic Warfare Department
15 January 1980

Under authority of
W. B. HAFF
Captain, U.S. Navy
Commander

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(U) This document is an analysis of the ability of the radiolocation service to share the 92- to 95-GHz band with the fixed, mobile, and fixed-satellite services. This analysis indicates that the required separation distances between radiolocation and the other services for limiting interference to acceptable levels are small and, hence, that sharing is feasible.

CONTENTS

INTRODUCTION

This document is an analysis of the ability of the radiolocation service to share the 92- to 95-GHz band with the fixed, mobile, and fixed-satellite services. The fixed service transmits information with radio waves between specified terrestrial fixed points; a radio-relay system for a telephone is an example. Transmissions between mobile terrestrial stations are used by the mobile service; an example is maritime radio. The fixed-satellite service transmits information between fixed terrestrial stations and satellites. Sharing is evaluated by calculating separation distances between stations which will limit interference to acceptable levels. This analysis indicates that required separation distances between radiolocation and the other services are small and, hence, that sharing is feasible.

At this time, this band receives only very limited usage by these services, all of it of an experimental nature. Understanding of propagation phenomena is incomplete, particularly the effects of rainfall. Achievable performance levels of equipments are as yet unknown. Thus, any evaluation of sharing in this band must be based on hypothetical equipment characteristics.

Telecommunication activities in this band will, in general, be characterized by large antenna gains and narrow beamwidths from relatively small apertures, large amounts of available bandwidth, and range limitation due to atmospheric attenuation. Wide-beamwidth antennas may be used for some short-range-terrestrial and earth-to-geosynchronous orbit transmissions. The small effective areas of receiving antennas with beamwidths greater than several degrees require large amounts of transmitted power, although array antennas may reduce the power requirements. Special consideration will have to be made for the effects of adverse weather and propagation anomalies. Energy transmission will be line of sight, and the usage of narrow antenna beamwidths will greatly reduce the occurrence of main-beam to main-beam interference.

Equipment characteristics for the radiolocation, fixed, mobile, and fixed-satellite services are assumed. Characteristics of existing systems at lower frequencies, projections of techniques to be used at millimeter wavelengths, and projections of component performance are used.

The ability of these services to share this spectrum is evaluated by calculating separation distances sufficient to limit interference to acceptable levels for the assumed system characteristics. Modulation rejection techniques are ignored in the evaluation of interference; all of the energy entering the antenna of the victim equipment, within its reference bandpass, is assumed to degrade the noise level of the victim receiver, irrespective of the modulation of the transmitted energy or

of the ability of the victim to reject this modulation. It should be noted that the peak power transmitted in pulse radar systems can be significantly greater than the average power, and this may cause problems for some types of victim receivers. On the other hand, significant rejection of this modulation may occur for some receiver types.

Ongoing technological development will play a significant role in the ability of these services to share the spectrum. For example, peak transmitter power may be limited for some time. As techniques for handling greater amounts of power are developed, range performance of radiolocation devices will improve, although significant increases in transmitted power are required for small increases in range performance due to the atmospheric attenuation. Significant experimental activities will be required by all proposed services before the feasibility and characteristics of operation in this band will be known.

Specific characteristics of radiolocation devices, such as the $1/R^4$ range dependence and the fact that atmospheric attenuation is experienced twice for a given range to target, dictate that the propagation windows such as the 92- to 95-GHz band be available. Other terrestrial services experience a $1/R^2$ range dependence and traverse a given path only once. Space services experience significantly less attenuation due to the atmosphere since they do not use horizontal paths in the atmosphere.

EQUIPMENT CHARACTERISTICS

Two radiolocation systems are postulated: a terrestrial pulsed radar system of high range resolution using a large antenna and an airborne radar using a small aperture. The terrestrial pulse radar is designed for purposes of precision tracking targets of approximately 1-square-meter cross section, such as small aircraft. Its field of view is assumed to be hemispherical. It uses a moderately large antenna and a reasonably good system noise figure.

A man portable system for communications using a small aperture and a narrow reference bandwidth is considered for the mobile service.

The fixed service is characterized by a link with large apertures and good, but not state-of-the-art, receivers. A link distance of 10 kilometers is assumed, since this will allow a 20-dB fade margin to be sufficient in a 2.5-millimeter-per-hour rain. The link is assumed to transmit digital data, which is consistent with the large amounts of bandwidth available.

The fixed-satellite service uplink is assumed to have a near state-of-the-art antenna and an excellent transmitter at the earth station. The space station is characterized by a narrow-beam antenna and a good

system noise figure. Allowable interference-to-noise (I/N) ratios established for the transmission of digital data from 15 to 40 GHz are assumed for the satellite service. The total attenuation in passing through the atmosphere is assumed to be 5 dB. This corresponds to the satellite appearing at 10 degrees above the horizon.

These postulated system parameters are discussed in Appendix A in greater detail.

SHARING ANALYSIS

The analytical techniques used in the sharing analysis are described in Appendixes B and C. The results of this sharing analysis are presented in Figures 1 through 6 and Tables 1 and 2.

TABLE 1. Terrestrial Radar as Receiver.
Separation distance in kilometers.

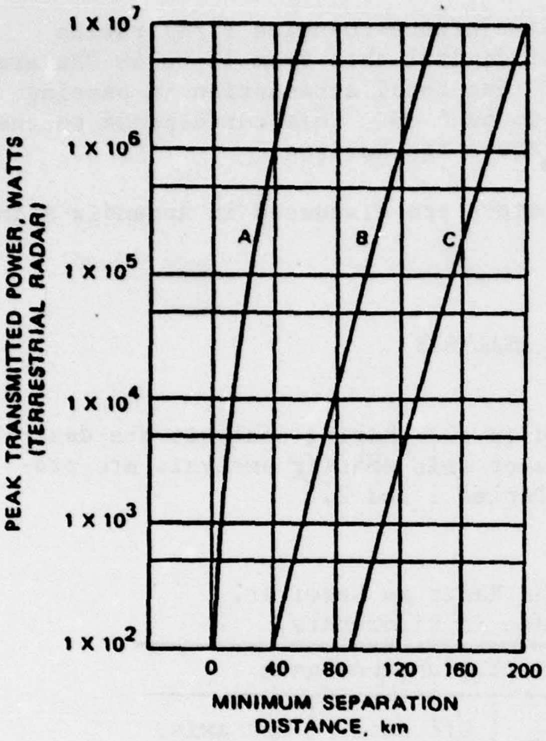
Emitter	Emitter antenna gain		
	Main beam	Off axis, 1 deg	Off axis, >48 deg
Fixed	33.5[a]	5.83[a]	0.06
Mobile	36.6[a]	27.0[a]	0.50
Earth-station	179[a]	92.3[a]	20.2

[a]Highly unlikely.

TABLE 2. Airborne Radar as Receiver.
Separation distance in kilometers.

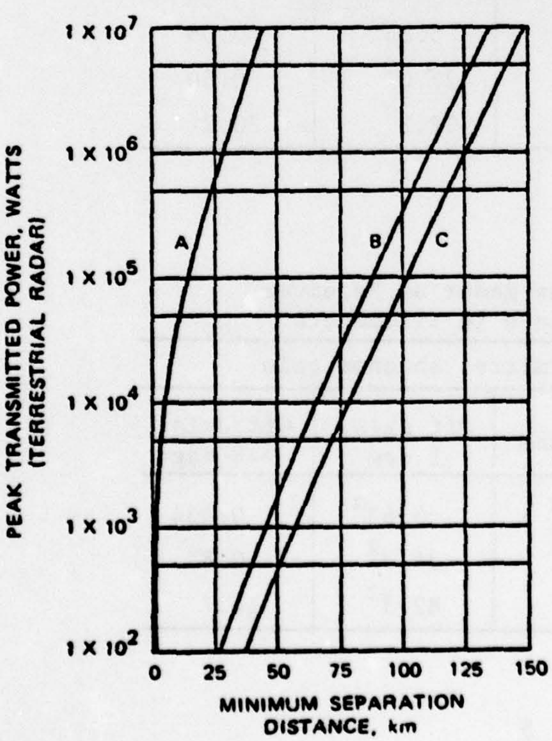
Emitter	Emitter antenna gain		
	Main beam	Off axis, 1 deg	Off axis, >48 deg
Fixed	26.3[a]	3.63[a]	0.034
Mobile	44.8[a]	34.3[a]	0.87
Earth-station	167[a]	82.3[a]	14.7

[a]Highly unlikely.



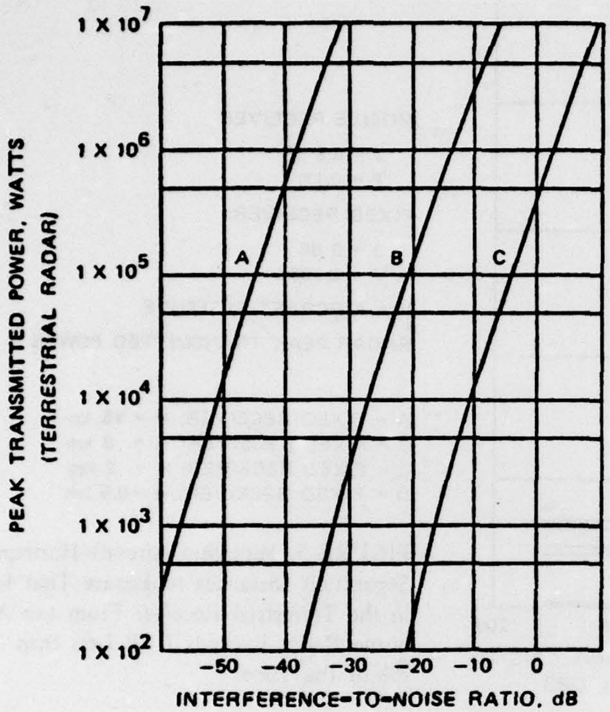
A = RECEIVED GREATER THAN 48 DEG OFF FIXED ANTENNA AXIS
B = RECEIVED 1 DEG OFF FIXED ANTENNA AXIS
C = RECEIVED THROUGH MAIN BEAM OF FIXED ANTENNA

FIGURE 1. Minimum Separation Distance to Ensure That I/N in the Fixed Receiver From the Terrestrial Radar Exceeds 0 dB Less Than 0.003% of the Time.



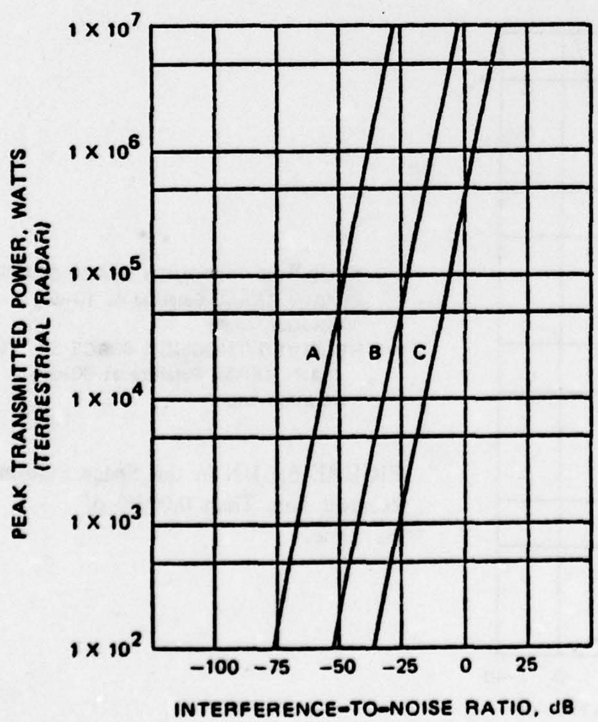
A = RECEIVED GREATER THAN 65 DEG OFF MOBILE ANTENNA AXIS
B = RECEIVED 1 DEG OFF MOBILE ANTENNA AXIS
C = RECEIVED THROUGH MAIN BEAM OF MOBILE ANTENNA

FIGURE 2. Minimum Separation Distance to Ensure That I/N in the Mobile Receiver From the Terrestrial Radar Exceeds 4.8 dB Less Than 0.1% of the Time.



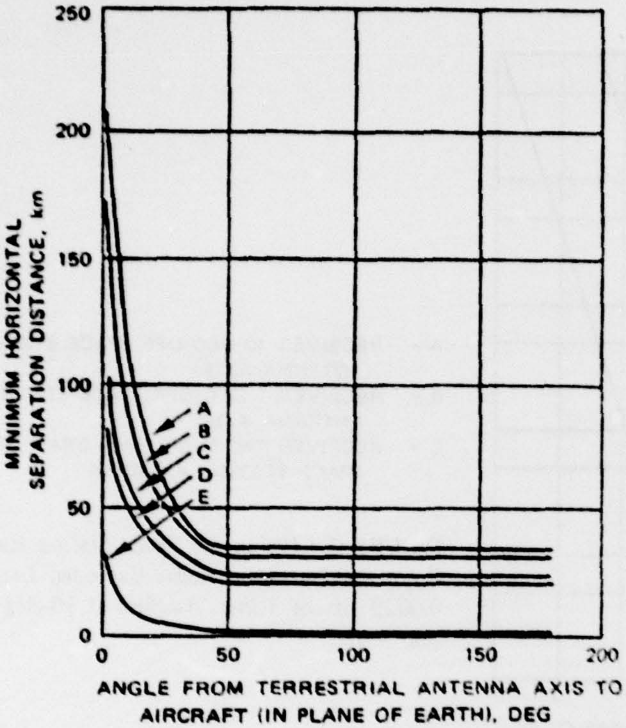
A = RECEIVED 10 DEG OFF SPACE STATION ANTENNA AXIS
B = RECEIVED 1 DEG OFF SPACE STATION ANTENNA AXIS
C = RECEIVED THROUGH MAIN BEAM OF SPACE STATION ANTENNA

FIGURE 3. I/N in the Space Station Receiver From the Terrestrial Radar Exceeded Less Than 0.003% of the Time. Satellite at 90-deg elevation angle.



A = RECEIVED 10 DEG OFF SPACE STATION ANTENNA AXIS
B = RECEIVED 1 DEG OFF SPACE STATION ANTENNA AXIS
C = RECEIVED THROUGH MAIN BEAM OF SPACE STATION ANTENNA

FIGURE 4. I/N in the Space Station Receiver From the Terrestrial Radar Exceeded Less Than 0.003% of the Time. Satellite at 10-deg elevation angle.



MOBILE RECEIVER

J = 4.8 dB
P = 0.1%

FIXED RECEIVER:

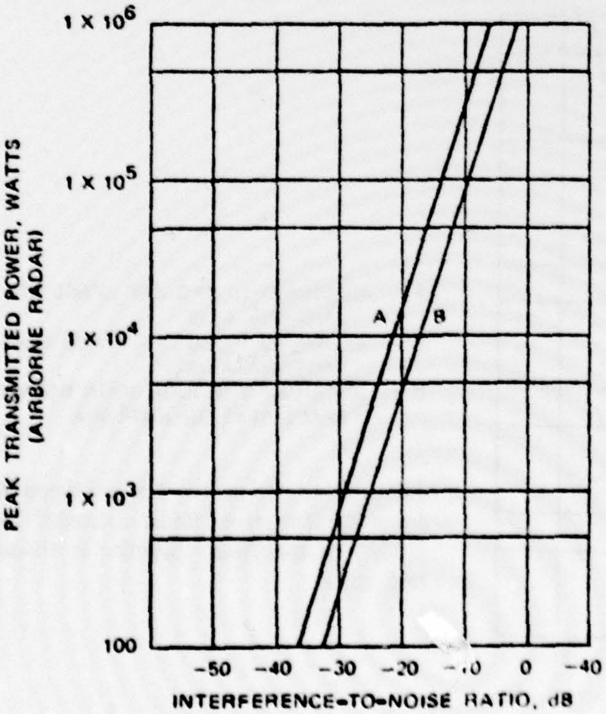
J = 0 dB
P = 0.003%

H = AIRCRAFT ALTITUDE

RADAR PEAK TRANSMITTED POWER – 60 kW

A = FIXED RECEIVER; H = 15 km
B = FIXED RECEIVER; H = 8 km
C = FIXED RECEIVER; H = 2 km
D = FIXED RECEIVER; H = 0.5 km

FIGURE 5. Minimum Aircraft Horizontal Separation Distances to Ensure That I/N in the Terrestrial Receiver From the Airborne Radar Exceeds J dB Less than P% of the Time.



A = RECEIVED THROUGH SPACE STATION MAIN BEAM. Satellite at 10-deg elevation angle
B = RECEIVED THROUGH SPACE STATION MAIN BEAM. Satellite at 90-deg elevation angle

FIGURE 6. I/N in the Space Station Receiver Less Than 0.003% of the Time.

DISCUSSION OF SEPARATION DISTANCES

TERRESTRIAL RADAR AS EMITTER

Sharing with the fixed receiver is feasible, since small separation distances are adequate if the fixed antenna points at least 48 degrees away from the radar. Separation distances of 40 kilometers are sufficient for radar power levels up to 1 megawatt.

Sharing with the mobile receiver is feasible as long as the mobile antenna is not pointed in the vicinity of the radar.

The terrestrial radar presents a threat to the space station only when in the space station's main beam at high radar power levels. In a sharing situation, increased earth station transmitted power could provide a margin against this interference, as could pulse rejection techniques.

TERRESTRIAL RADAR AS RECEIVER

Table 1 indicates that sharing with the earth station and the fixed transmitter is feasible. Small coordination distances are sufficient if these antennas are pointed more than 48 degrees away from the radar.

Sharing with the mobile transmitter is feasible since small separation distances result for any mobile antenna pointing direction.

AIRBORNE RADAR AS EMITTER

Sharing with the fixed receiver is feasible as long as the aircraft does not fly too near the main beam of the fixed antenna. This might be assured by establishing corridors around fixed links not to be overflown. Note that required separation distances (on the earth) increase with aircraft altitude for the altitudes considered here due to the decreasing atmospheric attenuation.

Sharing with the mobile receiver is feasible even when the aircraft is above the mobile antenna main beam. The small separation distances enable an aircraft to avoid areas of mobile operations.

Sharing with the space station is feasible since even very high-transmitted-power levels do not cause interference.

AIRBORNE RADAR AS RECEIVER

Required separation distances are small, as long as the aircraft does not fly near the mean beam of the earth station antenna. This

coordination is feasible. As modeled in this analysis, interference will occur only for a very small portion of the radar field of view and can be ignored if detected.

CONCLUSIONS

Radiolocation devices will benefit considerably from the high angular and range resolution, which are possible in the 92- to 95-GHz band. These devices require large increases in transmitter power to achieve small increases in range performance in this band (Figure 7). This is due, in part, to the 8-dB of atmospheric attenuation these devices experience for each 10 kilometers of range to the object being detected. The diminishing improvement in range performance with increased power and the difficulty in generating and guiding high-power levels at these frequencies may limit radiolocation devices to shorter ranges for some time.

The fixed and mobile equipments modeled in this document are not limited by available power or clear-weather atmospheric attenuation, but rather by performance requirements in adverse weather.

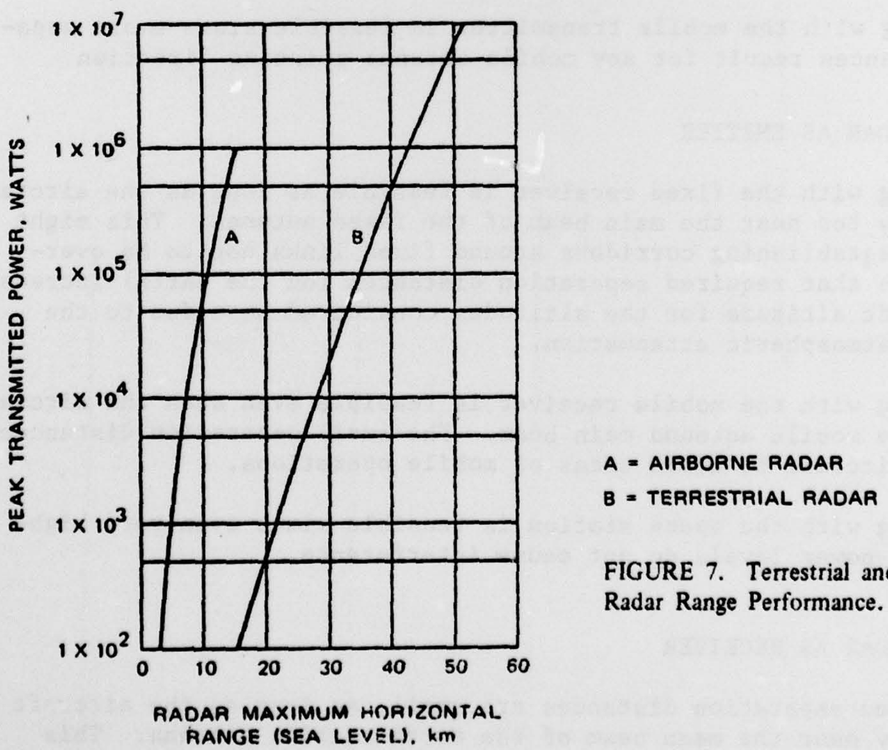


FIGURE 7. Terrestrial and Airborne Pulsed Radar Range Performance.

The sharing analyses indicate that, except for the highly unlikely presence of a radiolocation device near the main antenna beam of a fixed or mobile receiver, or of an earth station transmitter, required separation distances generally well under 40 kilometers between radiolocation and the other terrestrial devices result.

Line-of-sight limitations of millimeter-wave propagation may limit antenna coupling between terrestrial equipment at ranges in excess of about 50 kilometers, reducing required separation distances. Due to small equipment size and the line-of-sight nature of propagation, site shielding will be easy to implement and will be effective in this band.

The interference power from the terrestrial radar exceeds the allowed value in the space station receiver when the radar transmitted power exceeds about 400 kilowatts. It would be possible for the space link to provide a margin against this interference. Pulse-blanking techniques in the fixed-satellite equipment may also be available. The airborne-radiolocation device poses no threat to the space station at even high-power levels.

The similarity of separation distances obtained for a variety of equipment types indicates that they may be typical for sharing with radiolocation devices in this band.

The fixed-satellite earth-to-space link requires large amounts of power to overcome the $1/R^2$ spreading to the geosynchronous orbit and to allow sufficient energy to be collected by small apertures on the satellite. The total attenuation in passing through the atmosphere is less than 5 dB for earth stations positioned less than 72 degrees north or south latitude and is not a major contribution to the power requirement.

Appendix A

EQUIPMENT CHARACTERISTICS FOR RADIOLOCATION, MOBILE, FIXED, AND FIXED-SATELLITE SERVICES

Hypothetical system parameters for a pulsed-terrestrial-track radar, an airborne-pulsed radar, a fixed link, a mobile link, and an earth-to-space fixed-satellite link are presented in Table A-1.

TABLE A-1. System Parameters.

Parameters	Terrestrial radiolocation	Airborne radiolocation	Fixed link	Mobile link	Fixed-satellite (earth to space)
Transmitter					
Antenna diameter, m	2.0	0.32	1.0	0.15	5.0
Antenna efficiency	0.7	0.7	0.7	0.7	0.7
Transmitter power, W	...	...	0.034	0.24	31000
Losses, dB	5	5	5	5	3
Pulse width, effective, sec	10×10^{-9}	100×10^{-9}	...	...	...
Pulse width, transmitted, sec	10×10^{-6}	1×10^{-6}	...	...	...
Receiver					
Antenna diameter, m	2.0	0.32	1.0	0.15	0.32
Antenna efficiency	0.7	0.7	0.7	0.7	0.7
Required S/N, dB	20	13	20	20	20
Fade margin, dB	...	...	20	20	10
Losses, dB	5	5	5	5	5
Bandwidth, Hz	100×10^{6}	10×10^{6}	1×10^{9}	2×10^{4}	2×10^{9}
Noise figure, dB	10	15	10	15	10
Allowable I/N in reference bandwidth, dB	-6.8	-6.8	0	4.8	0
Percent time allowable I/N can be exceeded	a	a	0.003	0.1	0.003
Reference bandwidth, Hz	100×10^{6}	10×10^{6}	1×10^{6}	2×10^{4}	1×10^{6}
Link range, km	...	...	10	30	4×10^{4}

[a] I/N evaluated 1 degree off antenna axis.

TERRESTRIAL TRACK RADAR

The terrestrial track radar is assumed to use a large antenna and a small effective pulse width to provide high angular and range resolution (range resolution = 1.5 meters). Radars with greater range resolution will be feasible at these frequencies, but their range performance will be more limited by available power.

A 10-dB system noise figure is considered good by radar standards. The system bandwidth is determined by the effective pulse width, which is determined by the required range resolution. The transmitted pulse width is 1000 times longer than the effective pulse width, but has the same spectral content to reduce the peak transmitted power while maintaining the range resolution. The pulse-repetition frequency (PRF) is dictated by the requirement that no range ambiguities exist within twice the radar's maximum range (Rm), and is given by fp = c/4Rm, where c is the speed of light.

A required 20-dB signal-to-noise (S/N) ratio is assumed. This value is typical of tracking radar. A measure of an allowable interference-to-noise (I/N) ratio can be established by defining an acceptable degradation in the thermal angle (tracking) error of the radar. For this calculation, it is assumed that an angular error degradation of 10% is acceptable. This assumption results in an allowable I/N noise ratio of -6.8 dB, which is assumed received 1 degree off the radar antenna axis.

Figure 7 presents maximum horizontal range as a function of peak transmitter power for the pulsed radar. The radar is assumed to be tracking a target with a radar cross section of 1-square-meter, which is typical of small aircraft. Greater ranges will result at higher elevation angles due to the reduced atmospheric attenuation.

Since this is a tracking radar, no restrictions can be placed on the elevation and azimuth angles that will be scanned.

AIRBORNE PULSED RADAR

The airborne pulsed radar is designed to detect a target with a radar cross section of 1-square-meter for tracking or obstacle avoidance purposes. It takes advantage of the large antenna gain available from small apertures at these frequencies to provide high resolution.

Since this system must withstand the rigors of flight, a somewhat degraded 15-dB noise figure has been assumed. The assumed effective pulse width of 100 nanoseconds will provide a 15-meter range resolution. The transmittal pulse width is 10 times longer than the effective pulse width with the same spectral content to reduce the transmitted power. The PRF is determined by fp = c/4Rm. The required S/N ratio is typical of radiolocation devices.

It is assumed that a maximum degradation in angular track error of 10% is allowed; then a measure at the allowable I/N ratio for this device is -6.8 dB, which is assumed to be received 1 degree off the radar antenna axis. The allowable interference will depend in a detailed manner on the specific radiolocation system under consideration.

Figure 7 presents the required peak transmitter power as a function of maximum radar horizontal range at sea level. Greater ranges will result at higher aircraft altitudes due to the decrease in atmospheric attenuation.

MOBILE SYSTEM

This section discusses system parameters for a mobile link system designed for portable line-of-sight communications using small apertures and narrow bandwidth. This mobile link has been designed to operate to a maximum range of 30 kilometers. Line-of-sight ranges of this magnitude are difficult to find, and this consideration establishes the maximum range. A 20-dB fade margin has been designed into this system. At a 30-kilometer range, this fade margin will not be sufficient to guarantee operation in significantly adverse weather. For example, a 10-millimeter-per-hour rain cell 4 kilometers in diameter will cause an additional 20-dB attenuation.

This link uses a small, easily transportable antenna. A system noise figure of 15 dB has been assumed, as is consistent with a portable system. A 20-kHz system bandwidth has been assumed, which is consistent with voice communication requirements.

A required 20-dB S/N ratio is assumed, which is consistent with CCIR documentation.[1] Footnote 1 states that allowable interference levels for mobile systems correspond to a 14-dB S/N plus interference ratio. This is equivalent to an I/N ratio of about 4.8 dB. It is assumed permissable to exceed this interference level for 0.1% of the time. Peak radar power is used to calculate the I/N ratio.

FIXED SYSTEM

In this section, system parameters for a fixed link are discussed. This fixed link takes advantage of the high-data rates and narrow-antenna beams available at the 92- to 95-GHz frequencies. The link is

[1] International Telecommunication Union. *Signal-to-Interference Protection Ratios and Minimum Field Strengths Required in the Mobile Services*, by International Radio Consultative Committee, XIII Plenary Assembly, 1974. CCIR Report 358-2, Volume VIII. Geneva, Switzerland.

designed for rather short range, however, to make possible operation in a moderate (2.5 millimeter per hour) rain with a reasonable fade margin.

The assumed 1-meter antenna diameter provides a 3-dB beamwidth of about 0.25 degree. This beamwidth should provide good performance while not being so narrow as to cause alignment problems.

A required 20-dB S/N ratio is assumed. The allowable I/N ratios for digital transmissions in the 15- to 40-GHz frequency range expressed here are given in CCIR documentation.[2] It can be anticipated that the fixed service may take advantage of digital techniques in the 92- to 95-GHz band due to the large bandwidths available.

The assumed 10-dB receiver noise figure may represent a good but not state-of-the-art receiver at this frequency. System losses of 5 dB at the transmit station and 5 dB at the receive station are assumed for a 10-dB total system loss.

The 10-kilometer fixed link range is established by propagation phenomena rather than by power limitations. Path diversity will probably be used by the fixed service to overcome the additional attenuation due to heavy rainfall. Heavy rainfall tends to occur in isolated cells of limited diameter, and the passage of one of these cells between the transmit and receive station can cause an outage, requiring use of an alternate path. The assumed 20-dB fade margin will allow the 10-kilometer link to function if the entire 10 kilometers experience a 2.5-millimeter per hour rainfall. For this assumed link, attenuation due to rainfall greater than 20 dB will require a separate path. It should be noted that the assumption of a greater fade margin would allow extending the range of this link.

FIXED-SATELLITE LINK (EARTH TO SPACE)

This section discusses parameters of an earth station-geosynchronous satellite link designed to transmit large data rates from earth to space. This link takes advantage of the large bandwidth and narrow antenna beams available at these frequencies.

In this example, the earth station has been assumed to have a near state-of-the-art antenna. Somewhat larger antennas are used in the radio astronomy service, but these are expensive. Low system losses are assumed for the earth station.

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[2] International Telecommunication Union. *Determination of Coordination Area*, by International Radio Consultative Committee, XIII Plenary Assembly, 1974. CCIR Report 382-2, Volume IX. Geneva, Switzerland.

The assumed antenna diameter of 0.32 meter for the space station would create a 3-dB beamwidth of about 0.8 degree. This antenna would create a spot on the earth about 500 kilometers in diameter. The average transmitter power in this example includes a 10-dB fade margin to partially offset outages due to adverse weather. Diversity in earth stations will probably be required to give the desired degree of performance in bad weather.

A required 20-dB S/N ratio has been assumed. The assumed 10-dB space station system noise figure represents a good but not state-of-the-art receiver. The allowable I/N ratio specified in Footnote 2 for earth stations receiving digital information in the 15- to 40-GHz region is assumed to be valid for the space station receiver.

A 5-dB total loss passing through the atmosphere is assumed in evaluating required earth station transmitted power. This is the attenuation an earth station, at 72 degrees latitude, would experience in broadcasting to the geosynchronous orbit. The vast majority of earth stations will be closer to the equator and experience significantly less attenuation, increasing the received S/N ratio at the satellite. For example, an earth station at the equator experiences approximately 0.8 dB total attenuation through the atmosphere.

Appendix B

ANALYSIS OF FREQUENCY SHARING INVOLVING THE TERRESTRIAL RADAR

This appendix discusses the analytical approaches used in calculating separation distances required for sharing situations involving the terrestrial radar.

TERRESTRIAL RADAR AS EMITTER

Radar Antenna Cumulative Gain Analysis

Appendix A (see Footnote 2) specifies allowable I/N ratios for the fixed and fixed-satellite services as values which can be exceeded for stated percentages of the time. A similar interference criterion is assumed for the mobile service. These values are given in Table A-1. Thus, for example, interference power received by the fixed service can be as large as the receiver noise level up to 20% of the time, and can be 30 dB above the noise level no more than 0.003% of the time. These criteria can both be satisfied conservatively by demanding that the interference power from the radar not exceed the fixed receiver noise level more than 0.003% of the time.

The fraction of time the radar causes interference is dependent both on the radar modulation duty cycle, Pdc, and the radar antenna scan angle distribution. The antenna scan history will determine the fraction of time the receiver will experience radar antenna gain equal to or greater than any chosen value (cumulative gain function). The long-term interference to the receiver, which is exceeded for a fraction P of the time, will result from the radar antenna gain that is exceeded P/Pdc of the time, which can be determined from the cumulative gain function.

The terrestrial radar is assumed to intercept targets near the maximum radar range (Rm) and to track them until they again exceed the maximum range. It is assumed, for simplicity, that the target being tracked is equally likely to be found anywhere within the upper half of an ellipsoid with two axes equal to Rm and the third (vertical) equal to the maximum expected target altitude, H. Figure B-1 shows the ellipsoid centered on the radar.

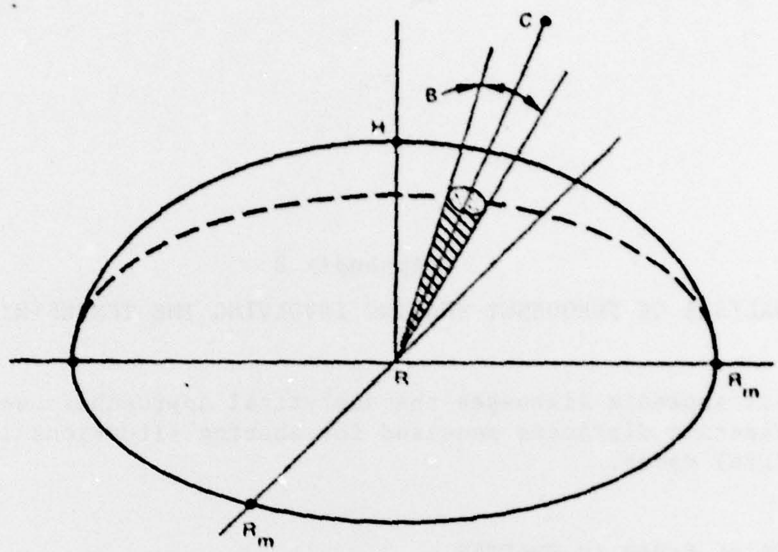

FIGURE B-1. Geometry for Terrestrial Radar Cumulative Gain Analysis.

The fraction of time the receiver experiences radar antenna gain equal to or greater than $G_r(\alpha)$ is given by the ratio of the volume of a cone of opening angle 2α with its apex at the radar intercepting the surface of the ellipsoid to the total volume of the ellipsoid (see Figure B-1). For purposes of simplification, the cone is assumed to be a pure right cone of length defined by the intercept of the cone axis with the ellipsoid. This approximation is valid for the small angles α encountered.

The reference radiation pattern for sidelobes of large antennas ($D/\lambda > 100$)[3] and extended to millimeter-wavelengths,[4] is used for the

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[3] International Telecommunication Union. *Characteristics and Maintenance of Earth Stations*, by International Radio Consultative Committee, XIIIth Plenary Assembly, 1975. CCIR, Study Group 4, Recommendation 465-1, Geneva, Switzerland.

[4] International Telecommunication Union. *Characteristics of Large Millimeter and Submillimeter Wave Reflecting Antennas*, by International Radio Consultative Committee, XIVth Plenary Assembly, 1978. CCIR, Study Group 1, Report 663, Kyoto, Japan.

fixed, terrestrial radiolocation, airborne radiolocation, earth station, and space station antennas. The reference pattern[5] for antennas with $D/\lambda < 100$ is used for the mobile antenna. This pattern is $G = 52 - 10 \log D/\lambda - 25 \log \phi$ to a minimum of $G = -10$, where ϕ is the off-axis angle.

Sharing With Fixed and Mobile Services

Separation distances can be calculated for various assumed values of receiver-antenna gain, transmitter-power levels, and receiver parameters. The radar antenna gain directed toward the receiver P/Pdc or more of the time, computed as described above, is used. Pdc is a function of the radar power since increased range performance requires longer intervals between pulses. Separation distance, as a function of radar-transmitter power for receiver antenna gain at off-axis angles of 0 degree (main beam), 1 degree, and the angle beyond which the reference-antenna pattern is a constant -10 dB, is presented. (See Figures 1 and 2.)

Sharing With Fixed-Satellite Service

The radar antenna gain, $G(\alpha)$, to be used can be found as described above. Interference-to-receiver noise ratios for geosynchronous satellites seen at elevation angles of 10 and 90 degrees from the radar for satellite antenna gain levels corresponding to off-axis angles of 0 degree (main beam), 1 degree, and 10 degrees (angular extent of earth disk from geosynchronous orbit) are calculated. (See Figures 3 and 4.)

TERRESTRIAL RADAR AS RECEIVER

Allowable interference levels and statistics for radiolocation devices will depend on the specific device in question. Terrestrial radar will most likely not make radar main-beam contact with fixed or mobile equipments due to radar scan geometries. Line-of-sight shielding may be demanded in radar applications involving safety of flight. Therefore, it is assumed that the radar antenna gain at a point 1 degree off axis is suitable for a conservative determination of separation distances. Separation distances required for sharing with fixed, mobile, and earth station transmitters are presented in Table 1. Antenna gains for these services corresponding to off-axis angles of 0 degree (main beam), 1 degree, and the angle beyond which the reference antenna pattern is a constant -10 dB are used.

[5] International Radio Consultative Committee. *Radiation Diagrams of Antennas for Earth Stations in the Fixed Satellite Service for Use in Interference Studies*, by CCIR Study Group 4. CCIR Report 391-2 (Rev. 76), 16 July 1976. Doc 4/215-E, Geneva, Switzerland.

Appendix C

ANALYSIS OF FREQUENCY SHARING INVOLVING THE AIRBORNE RADAR

This appendix outlines the analytical approach used to evaluate separation distances required for sharing with the airborne radar. Reference antenna radiation patterns used are described in Appendix B.

AIRBORNE RADAR AS EMITTER

Radar Antenna Cumulative Gain Analysis

The statistical antenna coupling between an airborne radar and a terrestrial or satellite receiver can be evaluated only with great difficulty. The coupling is dependent upon aircraft flight path statistics, airborne radar field of view, airborne radar antenna scan characteristics, radar duty cycle, and the antenna pattern of the receiver.

To simplify calculations, the radar antenna is assumed to be found with equal probability anywhere within the total solid angle sector scanned. The fraction of time $P(\alpha)$ that the radar antenna points within any angle α of boresight on the receiver is given by the ratio of the solid angle of a cone of opening angle 2α to the total solid angle scanned. The receiver can receive interference power greater than the allowed average interference power a fraction P of the time. The angle α is then determined by $P(\alpha) = P/P_{dc}$, where P_{dc} is the radar duty cycle. The radar antenna gain to be used in the sharing analysis is then determined from the appropriate reference antenna pattern using the value α.

Sharing With Fixed and Mobile Services

For this analysis, the radar is assumed to scan the lower hemisphere. Required separation distances on the earth for several aircraft altitudes as a function of azimuthal angle from the terrestrial antenna to the point on the earth below the aircraft are presented in Figure 5. The terrestrial antenna axis is assumed to be in the plane of the earth. A radar peak power of 60 kilowatts is used in this analysis.

Sharing With Fixed-Satellite (Earth-to-Space) Link

The spot size of the space station main beam is approximately 500 kilometers in diameter on the earth. Since the probability of

an airborne radar appearing in this spot is not negligible, the space station main-beam gain is used for conservative interference calculations. The probabilistic evaluation of radar antenna gain outlined above is used. The radar antenna is assumed to point at any angle with equal probability (spherical coverage). The I/N values occurring at the space station through the space station main beam for elevation angles of 10 and 90 degrees are shown in Figure 6.

AIRBORNE RADAR AS RECEIVER

An airborne radar will occasionally experience loss of track due to main-beam intercept of emitters in a sharing environment. Since it is not practical to eliminate this possibility and it has very small probability of occurrence, the radar sidelobe gain at off-axis direction of 1 degree has been used for conservative calculation of required separation distance. Required separation distances for fixed, mobile, and earth station transmitters are presented in Table 2. These separations are calculated for emitter antenna gains at off-axis angles of 0 degree (main beam), 1 degree, and the angle beyond which the reference antenna pattern is a constant -10 dB.

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